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Drivers' behaviour when overtaking cyclists on rural roads: Driving simulator validation using naturalistic data

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ABSTRACT

Driving simulator is a useful tool for obtaining data on driver behaviour efficiently and quickly. However, to ensure the reliability of the data gathered by the simulator, it is necessary to check the differences between drivers' behaviour in the simulator and in reality. In this study, an existing two-lane rural road was replicated on the driving simulator under the same traffic conditions of groups of cyclists and oncoming motorised vehicles. For this purpose, a naturalistic field data collection was developed on the real road using instrumented bicycles and static video recordings. A total of 30 volunteers participated in the driving simulator tests. The objective validation of the driving simulator was based on three operational variables: average travel speed, overtaking vehicle speed, and lateral clearance. As a result, higher average travel speeds and lower lateral clearances were obtained in the real world compared to those observed in the simulator. It was also found that overtaking vehicle speed depends on the group of cyclists. Overall, the data obtained in the field and in the driving simulator did not present statistically significant differences. The analysis of drivers' perception in the simulator tests concluded that the simulator reflected reality in an accurate way, achieving the subjective validation of the driving simulator. Thus, this study validates the driving simulator for bicycle safety research on rural roads.

1. Introduction

Road cycling is currently a common sport in many countries. In Spain, cycling is the second most practised sport and 63% of the population owns a bicycle (Ministerio Cultura y Deporte, 2021). It is very common to see sport cyclists riding on Spanish two-lane rural roads, both individually and in groups. In fact, in 2020 there were more than 3,600 federated cycling clubs in Spain (Ministerio de Cultura y Deporte, 2021).

Besides, two-lane rural roads represent 90% of the Spanish road network. Most of these roads do not have a specific lane for cyclists and some of them do not even have shoulders (Ministerio de Transportes Movilidad y Agenda Urbana, 2019). Therefore, cyclists usually must share the lane with motorised vehicles. In addition, the specific characteristics of cyclists, such as speed, volume, and level of protection, make the overtaking manoeuvre the most common and dangerous interaction between both types of road users. As a result, around 50 cyclists die every year on Spanish rural roads (Dirección General de Tráfico, 2020).

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One of the main objectives of the road authorities is to reduce the number of crashes involving cyclists on rural roads. To this end, several public awareness plans have been developed and policies have been implemented to increase bicycle safety on interurban environments, such as the construction of dedicated lanes or the signposting of roads with a high presence of cyclists. However, many rural roads on which cyclists regularly ride still do not have dedicated lanes and cyclists and motorised vehicles have to interact. Therefore, studies are needed to understand these interactions and enhance bicycle safety on rural environment.

Moreover, the presence of cyclists on two-lane rural roads also has an impact on traffic operation. Moll, López and García (2021) carried out a study based on field observations and traffic microsimulation focused on the effect on traffic operation caused by the presence of sport cyclists on Spanish two-lane rural roads. The results indicated that the presence of cyclists generally results in a worsening of the level of service of a rural road, decreasing traffic operation.

Cyclists on rural roads present an obstacle to motorised vehicles, creating the need for overtaking manoeuvres. Numerous studies have been conducted over the last decades to analyse overtaking manoeuvres to cyclists to identify the most influential factors. Different methodologies and tools have been used to collect data on overtaking manoeuvres, but most studies agree on the variables analysed: lateral clearance and speed of the overtaking vehicle. Rubie et al. (2020) conducted a literature review on the lateral clearance during the overtaking manoeuvre on rural roads, indicating that it is a very important variable in terms of objective and subjective safety.

Nevertheless, only a few studies considered groups of cyclists riding on rural roads, although it is a common phenomenon. Pérez-Zuriaga et al. (2021) analysed the main overtaking manoeuvre variables when drivers overtake cyclists riding in groups on five different two-lane rural roads. Higher lateral clearances but higher speeds of overtaking vehicles were found when cyclists groups rode in-line than two-abreast, identifying a higher compliance with the minimum passing distance required (1.5 m). In addition, more accelerative manoeuvres, with a previous following time, were observed when the group of cyclists rode two-abreast, especially on narrow roads. Fraser and Meuleners (2020) also studied groups of cyclists through naturalistic video recordings in Australia, concluding that the risk of an unsafe event was lower when cyclists rode two-abreast.

It is also important to analyse the risk perception of both motorised drivers and cyclists during the overtaking manoeuvre. To this regard, Rasch et al. (2022) analysed the perceived safety of drivers in a test-track experiment in Sweden and the perceived safety of cyclists in a field test in Spain. Bayesian ordinal logistic regression models of perceived safety scores were developed for both drivers and cyclists. The results showed that drivers' safety perception decreased with the presence of an oncoming vehicle with a low time-to-collision, while cyclists' safety perception reduced as lateral clearance decreased and overtaking speed increased. López et al. (2020) conducted a study about the risk perception of cyclists when they rode in a group of 10 cyclists. As a conclusion, cyclists who rode at the front or at the back of the group and in the lane side when rode two-abreast perceived the highest risk. In addition, cyclists' risk perception increased as lateral clearance decreased and overtaking speed increased, being these results in line with Rasch et al. (2022).

One of the most important points when conducting a study on road users' behaviour is the methodology used to collect data. Naturalistic driving observation provides a reliable picture of the normal driver's behaviour under real conditions (Winkelbauer et al., 2010). Naturalistic observations include instrumented vehicles and static video observations. Instrumented bicycles are often used to collect naturalistic data on overtaking manoeuvres (Beck et al., 2019; Chapman and Noyce, 2014; Garcia et al., 2020; Llorca et al., 2017; Moll, López, Rasch, et al., 2021). This method allows recording an important number of variables related to the overtaking manoeuvre such as lateral clearance, overtaking vehicle speed or overtaking duration. Nevertheless, collecting naturalistic driving data requires a long period of data collection and a great effort in terms of the required instrumentation and the personnel involved in the data collection and processing (Chuang et al., 2013).

Another usual method to collect data on drivers' behaviour when overtaking cyclists is driving simulator studies. To this regard, Bella and Silvestri (2017) and Mecheri et al. (2020) performed a study to analyse the effect of different cross sections and geometric elements of a two-lane rural road on drivers' behaviour during the overtaking manoeuvre to cyclists. Using this methodology, Bianchi Piccinini et al. (2018) analysed the influence of oncoming traffic on drivers' overtaking manoeuvres whereas Farah et al. (2019) modelled the overtaking strategy and the lateral distance during overtaking manoeuvres to cyclists. Also, Rossi et al. (2021) performed a study using a driving simulator to evaluate the impact of real-time coaching programs on drivers overtaking cyclists. Recently, Brijs et al. (2022) have conducted a driving simulator study to assess driver response to different Advanced Driver Assistance Systems (ADAS) with respect to overtaking a single cyclist and a pair of cyclists riding two-abreast.

There are some studies that compared drivers' behaviour between different collection data methodologies. Boda et al. (2018) compared the findings obtained from a driving simulator with those observed in a test track concluding that, despite the different gas pedal release behaviour, the results were very similar in critical situations. On the other hand, Kovaceva et al. (2020) compared the results obtained about overtaking manoeuvres to cyclists in a test track experiment and in a naturalistic driving study. Regarding this, drivers in the test track dataset drove in a more cautious and controlled mode than in the naturalistic driving environment.

However, there is no previous research comparing the behaviour of drivers during overtaking manoeuvres to cyclists between naturalistic and driving simulator data. In addition, although there are more studies that have used driving simulators to analyse different variables related to overtaking cyclists on rural roads, none of them have considered cyclists riding in different group configurations, which is a novelty in this study.

Thus, the main objective of the present study is to validate a driving simulator by analysing the differences between the behaviour of drivers when overtaking cyclists –riding individually and in groups– on a real two-lane rural road and in a driving simulator. To do this, the real two-lane rural road was recreated in a virtual environment that includes similar traffic conditions –groups of cyclists and oncoming vehicles– to the real road.

2. Methods

Two types of data related to overtaking manoeuvres to cyclists on a two-lane rural road have been used to carry out this study: (i) naturalistic data and (ii) driving simulator data. Both data collections were performed on the same rural road under similar traffic conditions. The validation of the driving simulator was developed by comparing the results obtained from both data collection methodologies.

Fig. 1 summarizes the research methodology. First, a naturalistic field data collection was developed on a two-lane rural road segment using instrumented bicycles and static video recordings located at the beginning and at the end of the road segment. Instrumented bicycles travelled along the rural road segment with different cyclist group configurations, collecting data of overtaking manoeuvres such as lateral clearance and overtaking vehicle speed. Simultaneous static video recordings were used to determine traffic volume and estimate, for each road user, its average travel speed (ATS) and the number of overtaking events. Secondly, the same road segment was recreated into a driving simulator, considering both geometric and traffic conditions from observations. Then, volunteers participated in the driving simulator experiment, driving the road segment and interacting with cyclists and oncoming traffic. As a result, diverse operational variables such as lateral clearance, overtaking vehicle speed, and ATS were calculated and then compared with those obtained from the naturalistic field data collection.

2.1. Road segment

The selected two-lane rural road segment is part of the CV-310 road, located in the Region of Valencia (Spain). This road segment has a length of 4,900 m –with no intermediate entrances or exits–, a longitudinal grade of 4%, and a posted speed limit of 80 km/h. The lanes are 3.2 m wide, while the shoulders are between 1.5 and 2 m wide and are red in colour (click here to visualize the road segment on Google maps: https://goo.gl/maps/WNuJoJogjMxswx718). The average annual daily traffic in 2021 was 5,830 vehicles per day. The road segment is characterized by a high cycle traffic volume, riding individually or in groups generally on the red shoulder.

2.2. Naturalistic observations

Naturalistic data was collected on the two-lane rural road using two different methodologies: (i) instrumented bicycles and (ii) static video recordings at the beginning and at the end of the road segment.

Instrumented bicycles were used to collect data during overtaking manoeuvres. Bicycles were instrumented with frontal and rear video cameras and laser devices to collect data during the entire overtaking manoeuvre considering all the phases described by Dozza et al. (2016): (i) approaching, (ii) steering away, (iii) passing, and (iv) returning. Cyclists who participated in the study were experienced road cyclists and made several trips on the road segment using the instrumented bicycles. Four group sizes of cyclists –individual, two, four, and ten cyclists– and two group configurations –in line (L) and two-abreast (TA)–, resulting in seven different group configurations were studied. A total of 474 overtaking manoeuvres involving passenger cars were recorded.

The lateral clearance and the speed of the overtaking vehicle were measured in the passing phase, i.e., when the overtaking vehicle was parallel to the cyclist(s). The duration of the overtaking manoeuvres was also calculated. Other variables such as type of overtaking vehicle, type of manoeuvre -flying or accelerative-, type of road centreline, lane encroachment, and the presence of oncoming traffic during the overtaking were also registered.

The second methodology for data collection on the rural road was based on simultaneous recordings at the beginning and at the end of the road segment. This methodology was used to obtain macroscopic traffic data, such as the average travel speed for each road user

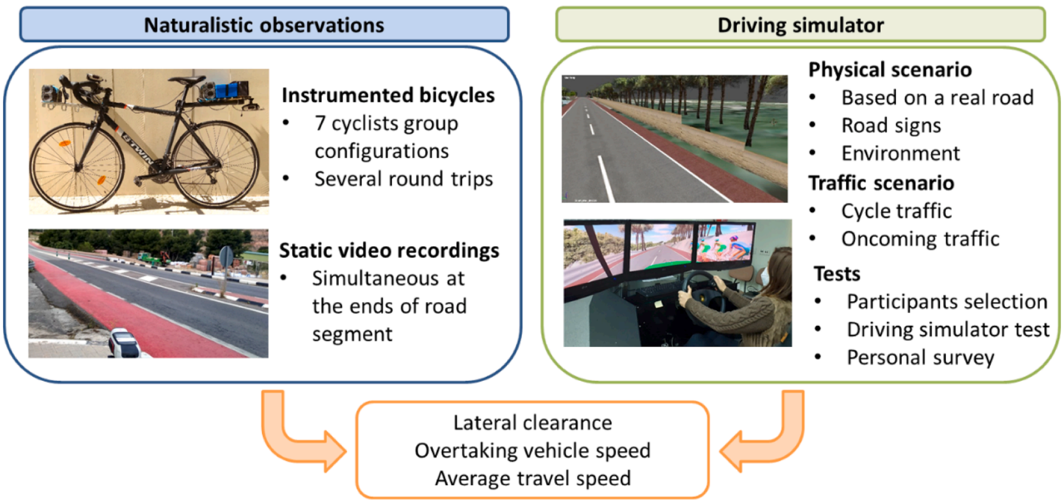

Fig. 1. Data collection methodologies and main variables.

(based on the entry and exit times of each user on the road segment) and traffic volumes for each type of user. After filtering the video recordings, data from 777 passenger cars and 287 cyclists were obtained. The distribution of the average travel speed of cyclists presented a mean value of 35 km/h and a standard deviation of 4.72 km/h. Table 1 includes the number of groups of cyclists registered by the static video recordings concerning their configuration –size and type– while Fig. 2 shows the distribution of frequency of drivers regarding the total number of overtaking manoeuvres performed along the road segment. Overtaking manoeuvres were calculated based on the order of entry and exit of each user on the road section. The overtaking manoeuvres concerned groups of cyclists, as cyclists tend to maintain their group configuration on roads without a longitudinal gradient. The group configuration of each group was also checked at the entry and exit points.

The development of the field data collection can be found in more detail in Moll, López and García (2021) where a thorough description of the instrumentation of the bicycles and static video recordings is presented.

2.3. Driving simulator experiment

The two-lane rural road segment was recreated in a virtual scenario for the driving simulator experiment. The driving simulator used, SE^2RCO, belongs to the Universitat Politècnica de València. The SE^2RCO is an interactive fixed-base driving simulator which consists of a simulation computer, which provides the graphics performance required for the implementation of the simulation software; data collection in real time; wireless router; three-screen-display monitors 1.80x0.34 m with 120° field of view; Matrox TripleHead2Go graphics card; sound stereo system; steering wheel, pedals, and gear shift of a Citroen Saxo; and generic adjustable seat. The developed programming environment is based on Visual C ++ 2008 Express to run in real time. The meshes of objects in the environment (traffic signs, trees, safety barriers, etc.) were generated using the 3D modelling Blender 2.70 and later. In addition to this, Python 3 was used to process data and calculations offline. nVidia PhysX library 3.2 was used to support vehicle dynamic and their behaviour with the collision system. The audio-visual section rests with the Microsoft DirectX 8.1 libraries specifically for Direct3D graphics rendering and DirectSound for sound reproduction.

The geometric characteristics of the road segment (length, lane and shoulder width, and horizontal and vertical alignment) were recreated using Autodesk Civil 3D while the traffic scenario was based on the observations performed during the naturalistic field data collection. The scenario generation procedure in the driving simulator can be found in Dols et al. (2021). Particularly, the traffic scenario with the maximum observed cycle traffic volume was simulated. In this scenario, a total of 38 cyclists rode on the road segment, grouped, in order of appearance, as follows: 15TA, 2L, 2P, 2L, 1, 1, 4TA, 1, 5TA, 2TA, and 3L. To this regard, the number indicates the quantity of cyclists in the group and TA or L indicates the type of configuration (two-abreast or in-line, respectively). In addition, the scenario was designed with oncoming traffic based on the traffic volume observed during the naturalistic study.

Fig. 3a shows a cyclist riding on the real two-lane rural road observed from a motorised vehicle. Fig. 3b shows a group of cyclists riding two-abreast on the driving simulator SE^2RCO. Finally, Fig. 3c shows a participant performing the driving simulator test.

Once the driving simulator scenario was ready, the participants were selected. They should be a representative sample of the Spanish driving population. For this purpose, participants were selected using data of drivers' population from the Spanish Directorate General for Traffic (DGT). The number of participants was estimated through Eq. (1), assuming a normal distribution of the average travel speed (ATS) of the drivers and hypothesizing a variability of the ATS in the driving simulator similar to that in the field study.

$$n = \frac{Z^2 \bullet \sigma^2}{e^2} \tag{1}$$

where n is the required number of drivers to conduct the study, Z is 1.96, associated with a 95% confidence level, σ is the standard deviation of the ATS measured in field in km/h, and e is the error assumed in the estimation of ATS (km/h). Given that the standard deviation of the ATS was 6.8 km/h and assuming an error of 2.5 km/h (Llopis-Castelló et al., 2019, 2016), the number of drivers needed to conduct the experiment was 28.

Finally, a total of 30 drivers performed the experiment, presenting Table 2 the distribution of drivers per age and gender. All drivers had driving license and signed a written informed consent.

The driving simulator test was divided into four phases: (i) instructions, (ii) training, (iii) test, and (iv) survey. First, drivers were informed that they might interact with cyclists along the road segment. Although drivers were not instructed on any specific travel speed, the virtual scenario had the same posted speed limits as the real road. Afterwards, a previous training round was conducted to introduce the participants to the driving simulator. Then, drivers performed the driving simulator test. This stage consists of a total of three scenarios with different motorised and cycle traffic conditions. The order in which the scenarios were travelled was randomised to avoid bias findings. Finally, drivers filled out a questionnaire on symptoms of adaptation to the simulation and the sense of realism while driving.

It should be noted that only the results of one of the virtual scenarios were considered for the validation of the SE^2RCO driving simulator.

Table 1
Cyclist groups registered according to the number of cyclists and configuration (L = in-line, TA = two-abreast).

Cyclists group configuration	1	2L	2TA	3L	3TA	4L	4TA	5L	5TA	6TA	8L	8TA	15TA
Number of groups	92	21	16	6	6	3	2	1	3	1	2	1	1

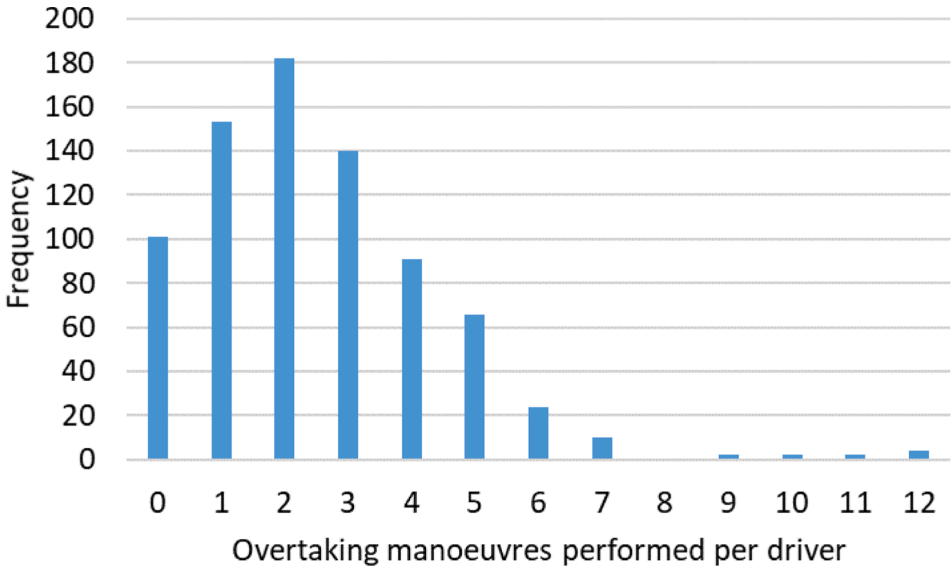

Fig. 2. Distribution of frequency of drivers regarding the number of overtaking manoeuvres registered by static video recordings.

Fig. 3. Images of: (a) real road, (b) road in the driving simulator, and (c) driving simulator test.

Table 2
Number of participants who carried out the driving simulator test per gender and age group.

	18–24	25–34	35–44	45–54	>55
Men	2	2	4	3	5
Women	2	2	4	3	3

2.4. Data filtering

The data of each driver during their travel on the road segment in the simulator were processed to calculate their trajectories and space–time diagrams.

Fig. 4 shows the trajectory of one driver (red line), where the overtaking to different groups of cyclists is clearly visible, presenting a variation in the lane position to increase the lateral clearance to the cyclists. Fig. 4 at the top also shows the curvature profile of the road segment (green line). This is important as the curvature can affect the lateral position of the vehicle on the road. There is also a variation in the width of the shoulder (dark green line). The lateral clearance calculations considered the position of the cyclists on the shoulder, as the width of the shoulder varies. In this sense, cyclists riding in-line rode in the centre of the shoulder, and those riding two-abreast rode 1 m apart and centred on the shoulder.

Fig. 5 shows the time–space diagram of a driver in the driving simulator test. The driver's trajectory is shown in red while the cyclists' trajectories are shown in black. The slope of each trajectory represents the speed. Cyclists were programmed in the simulator to ride at a constant speed of 35 km/h based on observed speeds in the field. Each group of cyclists was defined as homogeneous and placed at a specific station on the road segment. When the simulation starts, each group moves at a constant speed from its initial position. In this way, each driver interacts with each group of cyclists at a different road station that depends on driver's operation. The driver's speed varied along the road segment, slowing down and following some groups of cyclists before overtaking them.

2.5. Data analysis

Using Visual Basic programming, the environment in which each driver overtakes each group of cyclists in the driving simulator were identified. In each overtaking manoeuvre, the lateral clearance and speed of the overtaking vehicle were registered. The average travel speed (ATS) of each driver was also obtained. The objective validation of the driving simulator was carried out by comparing these data with those observed in the field data collection. Statistical tests were used to determine whether there were statistically significant differences between both datasets. The normality and homoscedasticity of all datasets was previously checked by the Shapiro-Wilk test and the Levene's test, respectively. To compare the cumulative distributions of the variables, the Kolmogorov-Smirnov (K-S) test was used.

The subjective validation of the driving simulator was carried out based on the data gathered in the questionnaires of the driving simulator tests. ANOVA tests were used to determine whether there were statistically significant differences in driver well-being and perception of the driving task, considering the gender and age groups.

3. Results

First, the objective validity of the driving simulator was studied by comparing three different measures of driver' behaviour interacting with cyclists: (i) average travel speed, (ii) lateral clearance, and (iii) overtaking vehicle speed. Next, the subjective validity of the driving simulator environment was analysed through the drivers' perception questionnaires.

Fig. 4. Road segment with geometric data and the trajectory of a driver along the driving simulator test.

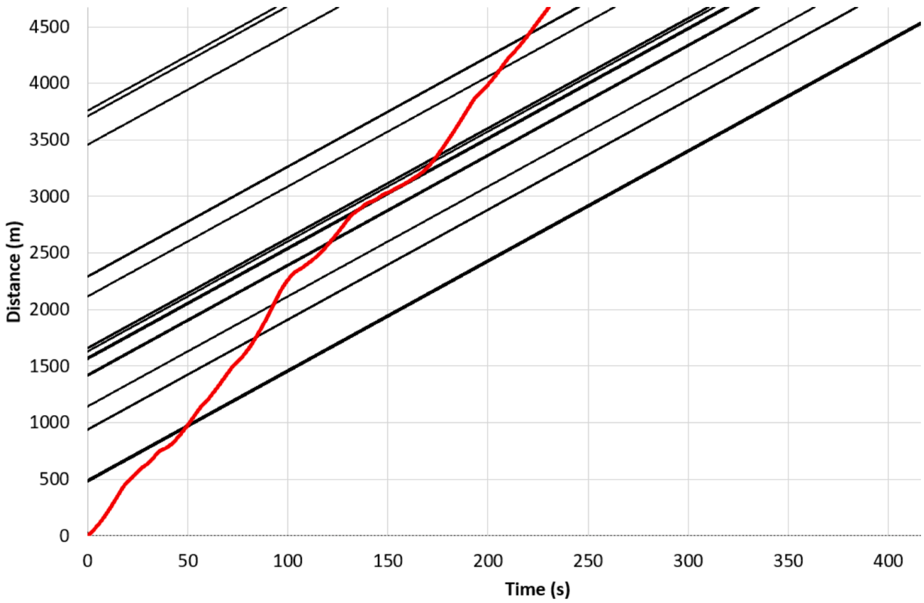

Fig. 5. Time-space diagram of a driver (red) and several cyclists (black) in the driving simulator test. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.1. *Average travel speed*

The average travel speed for each driver was calculated from the time taken to travel the entire road segment. Fig. 6 shows the distribution of the *ATS* obtained in the driving simulator (*ATS_Sim*) and in the field data collection (*ATS_Real*). The *ATS* in the driving simulator presented a mean value of 65.04 km/h and a standard deviation of 9.90 km/h, with a minimum value of 49.54 km/h and a maximum value of 90.96 km/h.

On the other hand, the *ATS* in the field data collection was obtained from the static video recordings at the beginning and at the end of the road segment. In total, the *ATS* of about 800 drivers was estimated. This dataset was very heterogenous because it consists of drivers who had not overtaken any cyclist to drivers who had overtaken 35 cyclists.

As previously indicated, the simulated traffic scenario corresponds to the maximum observed volume of bicycles, whereby drivers interacted with between 22 and 38 cyclists (depending on driver's speed and trajectory). Therefore, the *ATS* observed in the driving simulator was compared with the *ATS* estimated in the field under the same traffic conditions. Thus, the entire sample of real *ATS* was not considered, but only the real *ATS* values of drivers overtaking more than 20 bicycles. Additionally, the configurations of cyclist groups in the driving simulator were similar to those observed in the field data collection, with the largest group size being 15 cyclists.

In this way, a total of 49 drivers who overtook more than 20 bicycles were identified in the field data collection. The mean *ATS* of these drivers was 67.49 km/h and the standard deviation was 6.58 km/h, with a minimum value of 49.74 km/h and a maximum value of 81.8 km/h (Fig. 6).

The *ATS* recorded in the real world was, in general, slightly higher than that in the simulator, with a higher average value of 2.45

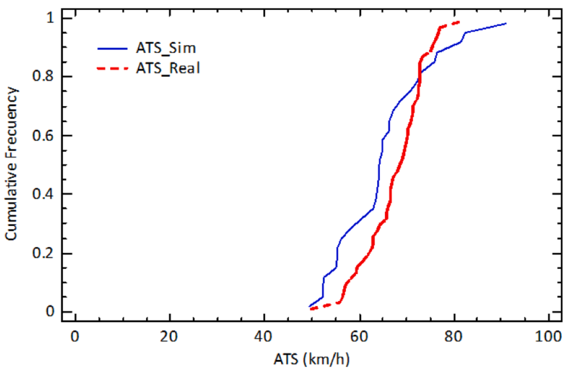

Fig. 6. Distributions of average travel speed registered on the driving simulator (*ATS_Sim*), and on the real road considering only drivers who overtake more than 20 cyclists (*ATS_Real*).

km/h. However, for high *ATS* values (>74 km/h), the *ATS* in the driving simulator was greater than in the real world. Despite the above-mentioned differences, the results of the *t*-test to compare the mean values between the two *ATS* distributions showed that there were no statistically significant differences at a 95% confidence level (t = -1.33, *p-value* = *0.189*).

The distributions of the two samples of *ATS* were compared using a K-S test. The results of the statistic showed a maximum distance between the two distributions of 0.299, and a *p-value* = 0.072, indicating that there were no statistically significant differences between both distributions at a 95% confidence level.

3.2. Lateral clearance

For the analysis of the lateral clearance, the following categories of the size of the group of cyclists and their configuration -in-line or two-abreast- were considered: (i) more than 8 cyclists riding two-abreast (Large group Two-Abreast, LTA), (ii) <8 cyclists riding two-abreast (Medium group Two-Abreast, MTA), (iii) <8 cyclists group in-line (Medium group in Line, ML), and (iv) individual cyclist (Ind).

The cumulative distributions of lateral clearances registered in the driving simulator and on the real road, considering the size and configuration of groups of cyclists, are shown in Fig. 7. It was observed that the lateral clearances obtained in the simulator were generally higher than those experienced in the real road. However, in some cases, especially for extreme values, the opposite trend was identified.

Table 3 shows a statistical summary of lateral clearance obtained from the driving simulator and from observations considering the different types of groups of cyclists. To this regard, the mean lateral clearance in the driving simulator was higher than in the real road for all cyclist group types.

All data sets were tested for normality using the Shapiro-Wilk test and for homoscedasticity using the Levene's test, and in all cases the *p-value* was higher than 0.05. Then, the *t*-test was performed to compare the mean lateral clearances obtained in the driving simulator and from field observations for the different cyclist group types (see Table 3). As a result, statistically significant differences were only identified for ML at a 95% confidence level. Moreover, K-S test was performed to compare the cumulative distributions of lateral clearances obtained in the simulator and in the real road (see Table 3). To this regard, statistically significant differences were only found between lateral clearance distributions for ML with 5% of significance level.

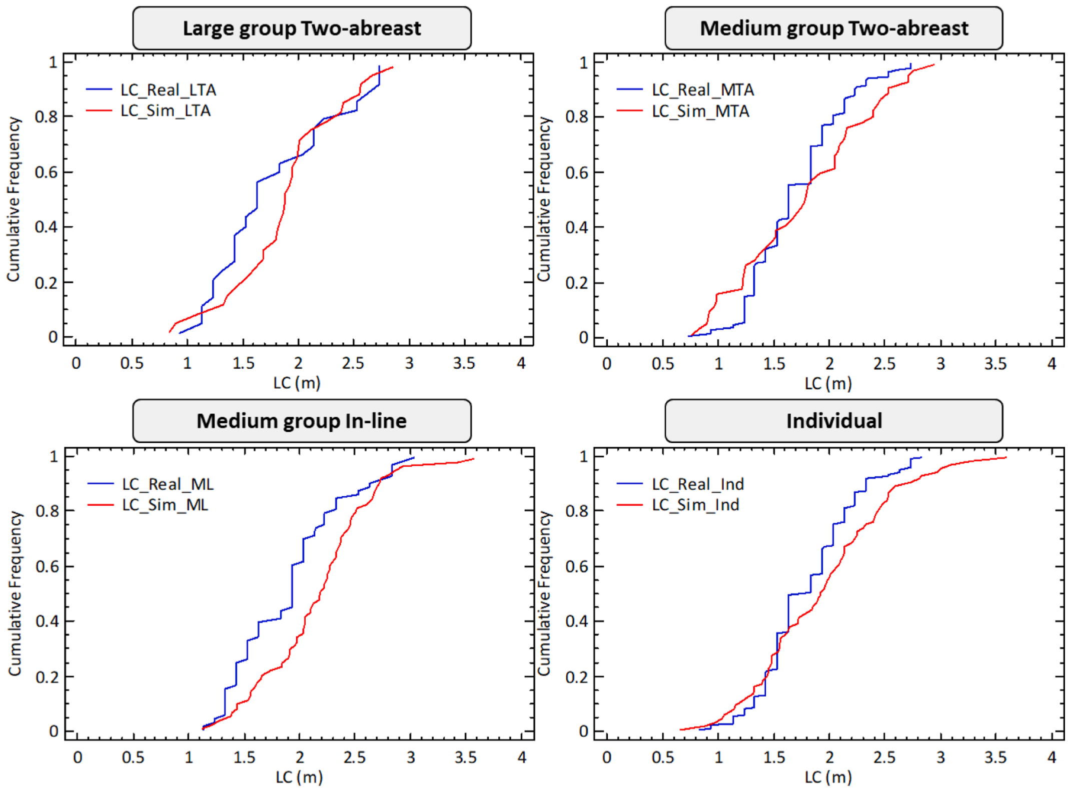

Fig. 7. Cumulative distributions of lateral clearances registered from simulator and from observations considering the size and the configuration of the groups of cyclists.

Table 3
Statistical summary and comparison test results for lateral clearance obtained from field observations and the driving simulator.

	Statistics					*t*-test		K-S test	
	N	Mean (m)	SD (m)	Min. (m)	Max. (m)	t	p-value	DN	p-value
Large Group Two-abreast									
Driving simulator	*30*	1.87	0.49	0.84	2.85	−0.768	0.445	0.314	0.099
Naturalistic observations	*31*	1.77	0.55	0.93	2.73				
Medium Group Two-abreast									
Driving simulator	*48*	1.76	0.59	0.76	2.95	−0.836	0.404	0.206	0.088
Naturalistic observations	*158*	1.70	0.41	0.73	2.73				
Medium Group In-line									
Driving simulator	*66*	2.15	0.49	1.12	3.58	−3.050	0.003	0.354	<0.001
Naturalistic observations	*74*	1.90	0.49	1.13	3.03				
Individual									
Driving simulator	*78*	1.93	0.59	0.66	3.60	−1.921	0.056	0.179	0.070
Naturalistic observations	*156*	1.80	0.42	0.83	2.83				

3.3. *Overtaking vehicle speed*

The analysis of vehicle speeds during overtaking was carried out considering the same types of groups of cyclists –LTA, MTA, ML, and Ind–. Fig. 8 shows the distributions of vehicle overtaking speeds for the different types of cyclist groups, with opposite trends observed when overtaking a large group of cyclists and an individual cyclist, and similar values for medium-sized groups of cyclists.

The results of the statistical parameters obtained are shown in Table 4. Regarding the mean values of vehicle speed during overtaking, higher mean values were obtained in the driving simulator than in the field study for all cyclist group types except when overtaking an individual cyclist. When only one cyclist was passed, lower speeds were recorded in the simulator than in the real road.

The normality of the data was checked using the Shapiro-Wilk test while the homoscedasticity was checked using the Levene's test. Then, differences between the mean values of the overtaking vehicle speed obtained from the simulator and from the field observations were analysed using the *t*-test. As a result, statistically significant differences were found for LTA and Ind, at a 95% confidence level (Table 4). However, the trend for both types of groups of cyclists was different. While for LTA the speed of the overtaking vehicles

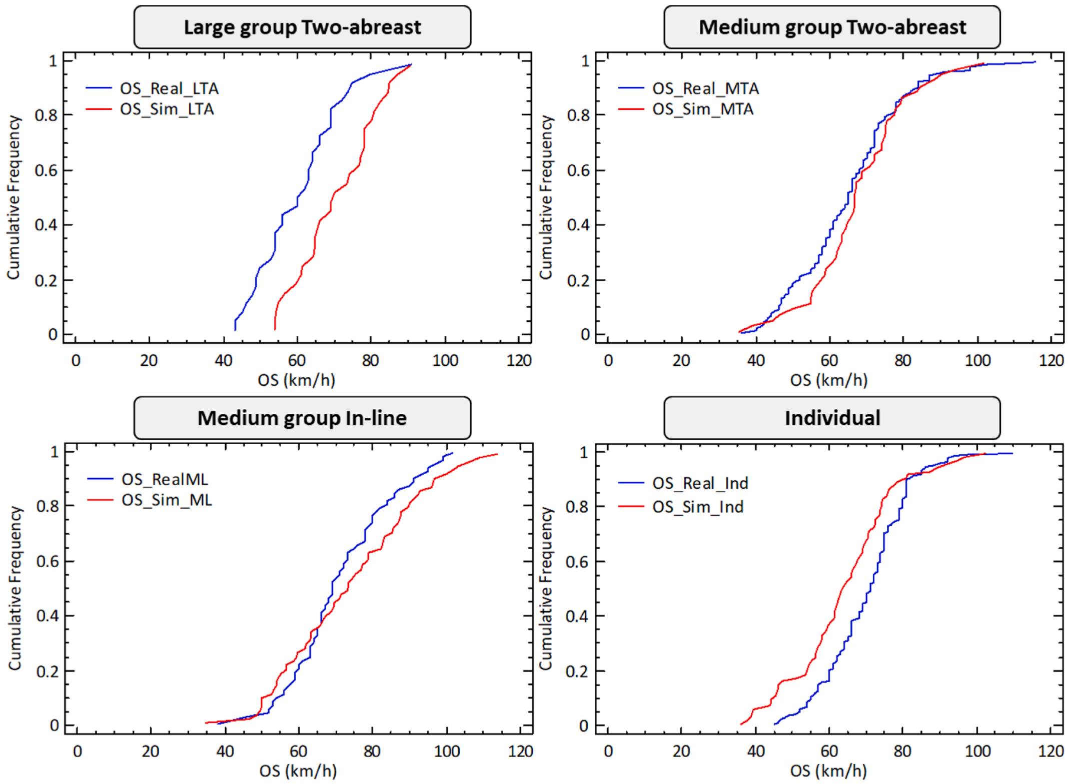

Fig. 8. Cumulative distributions of overtaking vehicle speed registered from simulator and from observations considering the size and the configuration of the groups of cyclists.

Table 4
Statistical summary and comparison test results for overtaking vehicle speed obtained from field observations and the driving simulator.

	Statistics					*t*-test		K-S test	
	N	Mean (m)	SD (m)	Min. (m)	Max. (m)	t	p-value	DN	p-value
Large Group Two-abreast									
Driving simulator	*30*	70.60	10.84	54.04	90.78	−3.623	<0.001	0.411	0.012
Naturalistic observations	*31*	60.23	11.50	43.00	91.00				
Medium Group Two-abreast									
Driving simulator	*48*	67.51	13.36	35.46	101.85	−1.037	0.301	0.147	0.410
Naturalistic observations	*158*	65.06	14.62	36.00	116.00				
Medium Group In-line									
Driving simulator	*66*	73.71	17.76	34.71	114	−0.983	0.327	0.161	0.329
Naturalistic observations	*74*	71.07	13.97	38.00	102.00				
Individual									
Driving simulator	*78*	64.02	14.03	36.04	102.51	3.610	<0.001	0.237	0.006
Naturalistic observations	*156*	70.12	11.17	45.00	110.00				

obtained from the simulator was higher than that identified in the field study, when only one cyclist was passed the speed in the driving simulator was lower.

The results of the K-S test were consistent with the mean tests, showing statistically significant differences between the distributions of vehicle speeds during overtaking large groups of cyclists and an individual cyclist, at a 95% confidence level.

When overtaking medium sized groups of cyclists, in line or two-abreast, there were no statistically significant differences between the mean values and between the distributions of vehicle speeds, at a 95% confidence level.

3.4. Drivers' perceptions

This section analyses the perceptions of the drivers who participated in the driving simulator study. These perceptions were collected using a questionnaire completed by each driver at the end of the test. The questionnaire consisted of two parts: (i) level of adaptation to the simulator and (ii) realism of the experience.

To measure the level of adaptation to the simulator, 11 items were assessed by the participants (general discomfort, fatigue, headache, eyestrain, difficulty in focusing, sweating, nausea, blurred vision, dizziness, vertigo, and stomach pain). Drivers indicated their perception in a five-level Likert scale, with 1 associated with a very good adaptation to virtual driving and 5 with great difficulty in adapting to the driving simulator. The Cronbach's alpha test was conducted to quantify the consistency and stability of this questionnaire, considering the 11 variables. As a result, a Cronbach's alpha of 0.92 was obtained, indicating a high degree of reliability and consistency of the questionnaire. The Cronbach's alpha coefficient was also calculated including these 11 variables for each gender separately, and for each age group. The results revealed high consistency in all cases with Cronbach's alpha coefficient higher than 0.7.

A mean value of adaptation was calculated for each driver as the average of the values of all items, thus preserving the same five-level scale. These values were below 1.85 for all drivers, indicating a good level of adaptation to the driving simulator.

The adaptation to the simulator was also analysed by age group using an ANOVA test (Table 5). As a conclusion, no statistically significant differences were found between the different age groups. However, analysing the results by gender, statistically significant differences were observed, with females showing higher difficulties to driving adaptation than males (Table 5).

Furthermore, drivers assessed the driving task in the simulator by rating on a five-level Likert scale, with 1 being very low and 5 being very high, the following items: (i) reality of the environment produced in the simulation, (ii) similarity in the driving task between the real world and the simulator, and (iii) natural and easy driving. The consistency and reliability of this part of the questionnaire was tested through the Cronbach's alpha coefficient, achieving a high consistency level ($\alpha = 0.81$). Finally, the mental workload in perceiving the road and adapting the driving was also measured on a five-level Likert scale.

In particular, the reality of the virtual environment was rated with scores higher than 3.5, indicating that drivers perceive the

Table 5
Results of driving simulator task test grouped by gender and age group.

	Driver gender				Driver group of age					
	Male (*N* = *16*)	Female (*N* = *14*)	ANOVA test		18–34 *(N* = *8)*	35–44 *(N* = *8)*	45–54 *(N* = *6)*	>55 *(N* = *8)*	ANOVA test	
	Mean	Mean	F	*p-value*	Mean	Mean	Mean	Mean	F	*p-value*
Adaptation	1.21	1.84	**11.42**	**0.002**	1.34	1.76	1.31	1.56	0.90	0.456
Reality	3.71	3.71	0.00	1.000	3.85	3.88	3.60	3.50	0.42	0.741
Similarity real world-simulator	3.21	2.93	1.12	0.300	3.14	3.13	3.20	2.88	0.27	0.847
Natural driving	3.36	3.07	0.67	0.420	3.43	3.50	3.20	2.75	1.08	0.377
Mental workload	2.93	3.57	4.10	0.053	3.00	3.38	3.40	3.25	0.26	0.852

simulated environment with high reality. Regarding the similarity in the driving environment between the real world and the simulator, the mean values varied between 2.88 and 3.25, indicating a medium–high degree of similarity. In addition, the drivers considered the driving task to be natural and easy, with a mean value of 3.21. Moreover, the drivers' mental workload was slightly high, with an average value of 3.25.

An ANOVA test was performed comparing these items by gender and age group (Table 5). Regarding the gender of the drivers, no statistically significant differences were found between males and females for any of the variables considered. Likewise, no statistically significant differences were observed in terms of driver age groups. These results point to an equality in terms of driver gender and age concerning the perception of the driving task in the simulator.

4. Discussion

Driving simulators are an interesting and effective tool for incorporating the human factor in traffic studies, both road safety and traffic operation, as they are capable of generating virtual scenarios where drivers provide a response similar to that developed on the real road. Driving simulators have important advantages over field data collection: lower costs, lower risk, faster and easier data collection, and control of a greater number of variables.

However, before being used in any research, driving simulators must be validated to generate reliable results (Llopis-Castelló et al., 2016; Underwood et al., 2011). The validation process, which consists of determining the degree of similarity between the driver's behaviour in reality and in the simulator, is usually divided into objective and subjective validation (Bham et al., 2014; Hussain et al., 2019; Wynne et al., 2019). Following these requests, this research validated drivers' behaviour when overtaking cyclists on a two-lane rural road in a driving simulator, comparing the results with real-world observations for objective validation and using a drivers' perception questionnaire for subjective validation.

Regarding the objective validation, Wynne et al. (2019) stated that a driving simulator is valid in absolute terms if the difference between variables obtained in the simulator and observed in reality is not statistically significant, and in relative terms if the simulator results show the same patterns or effects as real-world driving.

In this research, drivers' behaviour when overtaking cyclists was characterized by collecting variables related to the overtaking manoeuvre, such as lateral clearance and overtaking vehicle speed. Also, the Average Travel Speed (*ATS*) of each driver was obtained.

The lateral clearance is the physical space available between the motorised vehicle and the bicycle and is related to the collision risk (Llorca et al., 2017). Rubie et al. (2020) claimed that lateral clearance is critically important for objective and subjective safety. Therefore, the validation of this variable in the simulator is crucial to ensure the reliability of the conclusions and possible recommendations derived from studies using a driving simulator. The findings presented in this paper show that the lateral clearances obtained in the real road and in the simulator are similar, with no statistically significant differences for all types of cyclist group configurations, except for medium-sized groups riding in-line.

As for the *ATS*, greater variability was observed in the driving simulator. These results are in line with previous validation studies of driving simulators for speed research (Bella, 2008; Llopis-Castelló et al. 2016). This could be due to a lower perception of risk while driving in a virtual scenario. However, no statistically significant differences were found between the *ATS* obtained in the simulator and those observed in the real road. Thus, the driving simulator is considered to be objectively validated in an absolute manner regarding these variables.

However, the speed of the vehicle during overtaking manoeuvre presented different trends when large groups and individual cyclists were overtaken. Overtaking speeds in the simulator were higher than in the real road when drivers overtook large groups of cyclists. On the contrary, drivers who overtook an individual cyclist in the driving simulator travelled at a lower speed than on the real road. In this study, all overtaking manoeuvres have been considered together for a general validation of the driving simulator based on three operational variables: average travel speed, overtaking vehicle speed, and lateral clearance. However, it should be noted that there are other variables with great impact on the execution of the overtaking manoeuvre to cyclists, such as the presence of oncoming traffic or the available sight distance. These factors can influence the overtaking by generating flying or accelerative manoeuvres, and their analyses are proposed for more specific further studies.

Although there were no statistically significant differences for most of the types of cyclist group configurations studied, the values recorded in the simulator for lateral clearance were slightly higher and for *ATS* were lower than those observed in the field study. These results are in line with Kovaceva et al. (2020) that concluded that drivers drove in a more cautious and controlled mode while overtaking cyclists on a test track than in the real world. Boda et al. (2018) also compared drivers' behaviour when crossing cyclists at an intersection using a driving simulator and a test track. They obtained similar results in both data collection tools, especially in critical events, although a riskier behaviour was observed on the test track. The results of this study agree with Boda et al. (2018), identifying similar results in the simulator and the real world, but presenting a riskier behaviour in the real world.

Subjective validation of the driving simulator is an important issue as it is related to the level of realism perceived by the participants. Subjective validation is also called physical validation, as it corresponds to the physical and dynamic characteristics of the simulator and the visual system as perceived by the driver (Pawar et al., 2022). In this study, subjective validation was carried out by means of a questionnaire filled out by each participant at the end of the driving simulator test. Factors such as the reality of the virtual environment, the similarity in the driving task, natural and easy driving, and mental workload were assessed. The mean values obtained from participants' responses to the simulator test were in all cases higher than 3 in a scale between 1 and 5. This suggests that the level of realism achieved in the driving simulator is high, which subjectively validates the results obtained in the simulator. Looking at the data grouped by age groups, youngest drivers perceive the simulator as more realistic and more natural for driving, although no statistically significant differences were found between age groups. This may be due to the fact that these drivers are more accustomed to technology and virtual environments.

As Wynne et al. (2019) states, one of the main limitations of simulator studies is the sampling bias of the participants. In this study, we have tried to reduce this bias by selecting the sample size of participants based on the deviation in ATS observed. The gender and age range of participants was also selected based on official Spanish driver data. Therefore, the participants in the simulator test were selected on the basis of a representative sample of the current driving population in Spain. Wynne et al. (2019) also stated that an additional problem in simulator studies is simulator sickness. In this study, none of the participants showed high signs of symptoms of adaptation to the simulation, so all of them were included in the study. According to Wynne et al. (2019), the driving simulator must be validated for each particular study. Therefore, this work validates for the first time a driving simulator based on the behaviour of drivers when interacting with groups of cyclists on two-lane rural roads, obtaining suitable and reliable results.

It is clear that the use of driving simulators has many advantages for driver behaviour data collection. However, simulators also present some disadvantages and challenges. One of these limitations is the limited physical, perceptual, and behavioural fidelity of the simulated environment, which can produce invalid research outcomes. This aspect has been greatly improved in recent years thanks to the evolution of computational capabilities and possibilities. In this study, drivers' perception of the realism of the simulation was high, mitigating the effect of this limitation. Simulator sickness is also a limitation in the use of driving simulators. Although new generations of drivers are more familiar with the use of virtual environments, this effect needs to be assessed to validate the results. Another challenge is related to risk perception and driver motivation in virtual reality. Even if participants perform the task with the highest precision, they are aware that a collision in the simulated scenario will not cause any damage and, consequently, they would not be able to drive as carefully as in the real world (Caffò et al., 2020). This limitation is related to the possible outcomes of riskier driving in the simulator. Thus, the benefits of using simulators should be exploited, but the limitations and challenges of using simulators should also be considered and mitigated.

5. Conclusions

This study compares drivers' behaviour when overtaking cyclists riding in groups on a two-lane rural road in a driving simulator and in reality. A naturalistic field data collection was developed using instrumented bicycles and static recordings at the beginning and at the end of a rural road segment. The same road was recreated in a virtual environment, including the same geometric design and traffic conditions –cyclists riding in groups and oncoming traffic–. A total of 30 volunteers participated in the driving simulator test, representing the driver population in Spain.

Drivers' behaviour during overtaking manoeuvres to cyclists was studied from three operational variables: (i) Average Travel Speed (*ATS*), (ii) lateral clearance, and (iii) vehicle overtaking speed. *ATS* values presented similar results in both environments. The lateral clearance and vehicle overtaking speeds were analysed considering the size and configuration of the cyclist groups, concluding that no statistically significant differences exist between both environments in most cases. Regarding the vehicle overtaking speed, higher speeds were identified when overtaking large groups and lower speeds when overtaking individual cyclists in the simulator than on the real road, while for medium-sized groups the results were similar. Based on the results of this study, the driving simulator is considered validated for bicycle safety research on two-lane rural roads with mixed traffic of cyclists and motorised vehicles.

In addition, subjective validation was analysed by means of a questionnaire filled out by the participants in the driving simulator test. The results indicated that a high level of realism was achieved in the driving simulator, with no differences by gender and age group of the drivers.

The results of this study are limited to the characteristics of the simulated geometric and traffic scenarios. The validation process of the driving simulator is necessary to ensure the reliability of the results and the validity of the conclusions achieved. Once the simulator has been validated, it can be used to control and repeat the same conditions for different drivers in order to collect data quickly and efficiently. In addition, the simulator is ready to be used to simulate other traffic scenarios by varying the volume of cyclists and oncoming traffic, as well as to simulate other specific characteristics of cycle traffic, such as group size and in-line or two-abreast configurations. The development of flying or accelerative manoeuvres can also be analysed through factors such as oncoming traffic or available sight distance. Furthermore, by using a driving simulator it is possible to analyse how drivers react to different proposed countermeasures, such as modifications in road geometry and conditions (e.g., shoulder widening, lane narrowing, and incorporation of turnouts) or the effect of certain traffic regulations (e.g., speed limit variations).

CRediT authorship contribution statement

Sara Moll: Methodology, Investigation, Software, Formal analysis, Writing – original draft. **Griselda López:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Supervision. **David Llopis-Castelló:** Methodology, Investigation, Software, Formal analysis, Writing – review & editing. **Juan F. Dols:** Methodology, Investigation, Writing – review & editing. **Alfredo García:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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